A NEW CRYOGENICALLY COOLED 8.4 GHZ TRAVELING WAVE MASER FOR THE DEEP SPACE NETWORK

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ABSTRACT

Cryogenically cooled 8.4 GHz traveling wave masers (TWMs) operating in 4.5 Kelvin (K) closed cycle refrigerators (CCRs) on NASA Deep Space Network (DSN) antennas have achieved an input noise temperature (Tin) of 3.5 K with bandwidth over 100 MHz. This design has recently been adapted for operation in a 1.6 K liquid helium bath with a cryogenic feed system on a 34 meter beam waveguide antenna and has achieved an input noise temperature of 1.7 K at the feedhorn aperture.

An introduction to the DSN by descriptions of traveling wave maser (TWM) operation, the design 8.4 GHz TWM and a new ultra low noise 8.4 GHz liquid helium cooled maser/feed system (ULNA).

THE NASA DEEP SPACE NETWORK

The NASA Deep Space Network (DSN) is a world-wide system for tracking and communicating with spacecraft in earth orbits, on deep space exploration missions, and for radio science investigation of the solar system. The DSN is managed by the Jet Propulsion Laboratory (JPL) where much of the technology used for deep space communication has been developed.

The DSN evolved from missile tracking and data recovery techniques JPL developed for the U.S. Army in the 1950's [Ref.1]. In 1958 JPL established a three-station network of 108 MHz receiving stations to collect data from the first U.S. satellite, Explorer 1. The first maser amplifiers employed by the DSN in 1960 were used to track the Ranger spacecraft. These 960 MHz cavity-type masers were mounted at the prime focus of 26 meter antennas and liquid helium cooled to 4.2 K. The masers required periodic filling from a portable liquid helium dewar lifted into position beside the maser. In 1962 the DSN frequency was moved up to 2.3 GHz and traveling-wave masers continuously cooled in closed-cycle refrigerators were developed for

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cassegrain antennas. In 196"/ the fi st 64 meter station was completed and was used at S- Band for the. Mariner mission to Venus. In 1 973 8.4 GHz (X- Band) masers were installed on the. 64 meter antennas and used to track Mariner 10. By 1989 the 64 meter antennas were increased in diameter to 70 meters, increasing gain by almost 2 dB to 74 dBi. in addition to the current 2.3 GHz and 8.4 GHz spacecraft downlink frequencies, masers operating at 15 GHz and 22 GHz have been developed and used on DSN antennas for radio science applications. In January, 1993 a 33 GHz cavity maser was used for the fi st reception Of Ka-Band signals from deep space [Ref.?].

Today, the DSN is comprised of twelve deep space antenna stations in three Deep Space Communication Complexes (DSCCs). The Madrid, Spain Complex, the Canberra, Australia Complex, and the. Goldstone Complex in Southern California's Mojave Desert are each located about 120° apart in longitude, so as the Earth revolves, ii spacecraft can be tracked by each of the stations successively over a 24 hour period. 'The Network Operations Control Center is located at J]'], in Pasadena, California. (fig. 1).

Each complex is equipped with a 70 meter (230 foot) diameter antenna which is mainly used for deep space communication, ii 26 meter (85 foot) antenna used primarily for selected Earth orbital missions, and two 34 meter (1 1 ? foot) antennas which are used for both deep space and Earth orbital missions. The 70 meter antenna at Goldstone (DSS-14) is also used for planetary radar investigations. Stations can be "arrayed" or electronically combined to increase sensitivity or for Very Long Baseline Interferometry (VLBI), in which a virtual ante.nna is created with an effective diameter equal to the distance between the component antennas.

These antennas are cassegrain designs employing subreflectors to focus the micro wave signal at a feedhorn which extends from a "cone" housing the LNAs and the associated waveguide feed system and is attached to the surface of the. primary reflector (fig. 2). Components located inside the cone (and other components located on structures above the main elevation bearing) are subject to the tipping motion of the primary reflector as it links signal sources from the horizon toward zenith and then back to the horizon. After the initial amplification by the LNA, the signal is conducted past the main elevation bearing to receivers and downconverters below the cone via coaxial cable.

At Goldstone DSS-13 a new 34 meter beam waveguide (BWG) antenna has been erected for research and development purposes, and to help determine the design of future antennas. A beam waveguide antenna differs from a cassegrain design in its use of a series of flat and shaped "mirrors" to guide the microwave beam from the primary reflector and subreflector through a hole in the surface. of the main reflector and down a "tunnel" that bends around the elevation bearing to the microwave feedhorn at a stationary, non-tipping location. This design allows maximum flexibility in front end components installation because the final mirrors can be moved to focus on a variety of LNA feeds, and the space available for maser amplifiers, transmitters, etc. is much greater than is available inside a feedcone (fig. 3). The X-Band ULNA maser, described in this article, was designed to take advantage of the special properties of this design, providing the lowest possible noise temperature performance for a DSN amplifier/fed system.

Low Noise Amplifiers (LNAs)

Due to the size and weight restrictions imposed on spacecraft, the attendant small antenna size. and low transmitter power combine to make signal reception on Earth extremely difficult. As missions have extended into deeper space the technical challenge of recovering the small spacecraft signal from the nearly overwhelming noise has resulted in the development of ever larger and more. efficient antennas and driven continued research into low noise amplifiers (LNAs) which contribute the lowest internal electronic noise possible.

The signal-to-noise-ratio of a signal received by a DSN antenna is affected primarily by 1) the collecting area and efficiency of the antenna, 2) noise contributions from the atmosphere and cosmic background radiation, and 3) the internal noise contributed to the signal by the microwave feed system and LNA.

A figure of merit (M), which describes the sensitivity of a ground system (at a specific frequency) to a spacecraft downlink is directly proportional to the antenna area and efficiency (G), and is inversely proportional to the system operating temperature (Top), which includes LNA/feed microwave, noise. temperature performance:

$$M = G/Top \qquad [1]$$

To date, the lowest noise temperature LNAs used by the DSN are "maser" amplifiers, an acronym for Microwave Amplification by Stimulated Emission of Radiation. Masers provide the lowest equivalent input noise temperature (Tin), of any microwave amplifier, and in the DSN range from 2 K at 2300 MHz (S-band) to 3.5 K at 8450 MHz. For applications with less stringent noise temperature requirements or increased bandwidth, the more economical High Electron Mobility" Transistor (HEMT) amplifiers cooled in 15 K CCRs are used. HEMT LNAs in the DSN provide 4-5 K input noise temperature at 2.?-2.3 GHz and 10-12 K at 8.2-8.7 GHz have been used.

Various maser designs utilizing ruby material in reflected- wave, traveling wave, and cavity structures have been designed and used on DSN antennas [Ref. 3] This section will specifically address two re.cent maser designs: the DSN Block II-A TWM/CCR and the liquid helium-cooled X-band ULNA, which are traveling-wave designs.

The six main components of these maser assemblies are: 1) one or more traveling-wave maser amplifier stages, 2) the maser pump source which operates at ambient temperature, 3) a persistent-mock superconducting magnet which surrounds the maser channels, 4) refrigeration apparatus which cools the. mast.r and superconducting magnet to its operating temperature, 5) the vacuum jacket ant] radiation shields which provide thermal isolation, and 6) a low-noise cooled signal input. Each component will be described in detail below.

Block II-A X-Band Maser

The Block II-A is the lowest noise temperature X-hand operational Maser used in the DSN [Ref. 4]. These cryogenicall y cooled 8.4 GHz 'J'rave.ling Wave Maser Amplifiers were first implemented in the DSN on 70 meter and 34 meter antennas to track the two Voyager spacecraft on their tour of our solar system. The 9 Block 11-A TWMs currently in the DSN have a nominal equivalent input mist temperature of 3.5 K and over 1()() MHz of -3 dB bandwidth centered at 8450 MHz with 45 dB gain. Typical Block 11-A maser installations on the DSN 70 meter cassegrain antennas have two rectangular waveguide feed paths: a path which employs a diplexer to isolate the transmitter from the maser and provides a total system operating noise temperature (Top) of 30.5 K including cosmic background noise and atmospheric contribution with antenna at zenith, and a "low noise" path which bypasses the diplexer and has achieved a Top of 20.5 K, A special version of this maser used for planetary radar reception containing a cryogenic polarizer and a low 10ss circular waveguide input provide.s a Top of 14 K.

DSN TWMs use ruby as a paramagnetic material which is capable of producing a negative resistance, or amplification, when the following conditions arc met: the ruby must be cooled to cryogenic temperatures to reduce thermal energy; a shaped DC magnetic field provided by a superconducting magnet is applied through the ruby at the. appropriate angle; and the ruby must be excited, or "pumped", by microwave energy at the correct frequencies, and the. input signal must be appropriately coupled to the ruby maser. Each individual maser channel is an amplifier which produces 10- 12 dB of net gain. Four channels are connected in series by short coaxial cables which extend outside the superconducting magnet. The four amplifiers in cascade achieve the desired gain-bandwidth product of 40-45 dB net gain with 100 MHz bandwidth.

The basic Block II-A maser structure consists of one or more channels 34 cm in length machined from tough pitch electrolytic copper, each dielectrically loaded with a sapphire bar spacer, a slow-wave comb structure attached to the ruby bar, a resonant isolator assembly attached to alumina supports, and a full length spring to force the components against one side of the maser channel. (fig. 4).

DSN ruby is comprised of single. crystal aluminum oxide doped with ().()5% to ().()7%, chromium oxide. It is cut into bars so the axis of symmetry, known as the "C" axis, will be oriented to the magnetic field at the. proper angle for maser operat ion, usuall y 90° (54 .7° is also used)[Ref. 5].

Block 1 I-A type traveling wave masers employ a "slow-wave comb" structure. to delay the propagation of the incoming signal wave through the ruby. A 8.5 cm array of half-wavelength stripline copper conductors, each approximately .49 cm long, .1 cm wide and spaced .1 cm apart on the ruby bar with a coaxial input and output. Tough pitch electrolytic copper is used to fabricate the maser body and comb because of its low surface resistivity at cryogenic temperat ures. Cryogenic tests performed at JP1. have revealed the superior conduct ivit y of tough pitch electrol yt ic copper over oxygen-free half-hard copper (OFHC), even though OFHC specifications for resistive chemical ingredients arc more restricting. Sapphire was selected for use as the dielectric element next to the hand-glued comb because it provides less forward loss to the signal than alumina and has the same thermal coefficient of expansion as the ruby bar, thus avoiding possible abrasion as the components arc thermally cycled.

A unique Yttrium-Iron-Garnet (YIG) staggered height distributed isolator has been developed at JPL to suppress reverse gain, preventing amplifier regenerat ion and oscillation. The isolator provides high reverse loss at the signal frequency with low forward loss (Table 1). The resonant isolator elements are positional between the slow wave comb "fingers" in the area of maximum circular polarization '1 'hey are separated from each other by larger "shunt" elements which reduce the magnetic field through the resonant elements, thereby allowing, them to be physically smaller and thus provide lower forward loss.

The superconducting magnet (SCM) which surrounds the maser and supplies the 5 Tesla (5000 Gauss) magnetic field is constructed of wire which contains a niobium-titanium (NbTi) core ().()12.7 cm (.(X)5 in.) diameter surrounded by a copper jacket 7.631 {-3 cm (.003 in.) thick and coated with Formvar insulating varnish. Approximately 1500 turns are close-wound onto a copper form which fits neatl y around the four- channel maser bod y."1 'he maser body and coil arc contained within a 1 lyperco iron box which increases the magnetic field strength and provides a uniform field. The superconducting magnet operates at 4.5 K and is persistent to 9.5 K, The current required to charge. the magnet to 5 Tesla is 7 Amperes at less than 1 Volt. Magnet current is adjusted by a current supply connected across the coil. The magnet current is shunted through the power supply by driving a section of the coil "normal" using a small light bulb contained within a 4.5 K housing, then adjusting the current on the power supply. Turning the light bulb "switch" off allows the coil to return to a persistent mode and the power supply can be turned off. (fig. 5)

The DC magnetic field acting upon the maser body is shaped by steel shims attached to one side of the copper maser body. The steel shims effectively increase the field strength over part of the length of the maser and broadens the frequency range of the. ruby energy absorption. Maser gain is traded for increased bandwidth by adjusting the amount of magnct ic field staggcring. 'J 'he maser pump power is spread moss the ruby absorption band by deviating the center frequency of the pumps. The modulation rate of 1 (X) KHz allows pump power to stimulate maser amplification simultaneously at another frequency because the "relaxation" time of the ruby spins (@ 50 ms) is greater than the pump power sweep rate. @100 mW of pump power is required over 19.1 to 19.3 GHz and @ 200 mW is required over 23.9 to 24.2 GHz. The pump power enters the maser channel through a dielectricall y-loaded port from a cavity common to all four channels. The maser pump source is mounted outside the maser vacuum jacket and is connected to the maser via thin wall stainless steel waveguide to reduce heat leakage to the 4 K heat station. To improve electrical conductivity the interior of the waveguide is copper plated to a thickness of 2.3E-4 cm (90 microinches).

'l'he TWM/superconducting magnet assembly is mounted to and conduction cooled by a 4.5 K closed-cycle helium refrigerator (CCR) (fig. 6). The helium CCR originally developed by Arthur D. Lit tic, inc. in 1962 has been the basis for development of 4.5 K refrigerators at JPL. These CCRs employ a two- stage Gifford-McMahon refrigerator to attain stage temperatures of 70 K anti 15 K. A Joule-'l'homson expansion valve circuit using counterflow heat exchangers provides a 4.5 K third stage with a cooling capacity of over one Watt. The DSN currentl y uses 3 and 5 horsepower (HP) helium compressors to supply the 2 1X Pa (300 PSIG) helium gas ut ilized by the CCR. Compressors are connected to the maser CCR by 1.27 cm (.5 in.) flexible gas lines, anti are located up to 100 meters away from the maser/UX.

Radiation shields covering the cold stations arc gold plated to provide minimum radiation heat 10ss anti protection from corrosion. The vacuum inside the maser dewar is maintained by a Varian VacIon 8 liter/sec. pump at an operating pressure < 1331 [-5 Pa (1 0E-8 "roll").

The low noise signal input waveguide offer's low electrical]0ss but high thermal resistance, adding only ().3 K to the maser noise temperature. The unique "folded" design increases the resist ive pat h for heat leakage into the refrigerator while keepi ng the waveguide length short. Microwave choke joints separate the copper waveguide 3(K) K ,70 K, and 4.5 K sections thermally, and are supported by thin wall stainless steel tubes which are doubled back to increase their length (Ref. fig. 6). Output waveguides are .01()" wall stainless steel pieces copper plated inside 2.3E-4 cm thick for low loss. To further reduce the loss of the waveguide sections they are also conduction cooled by attachment to the 15 K and 70 K radiation shields.

X-Band Ultra Low Noise Amplifier (ULNA) Maser

The spacious, non-moving, easily accessible pedestal room afforded by the beam waveguide design of the 34 meter antenna at 11SS-13 allows use liquid helium cryostats as a practical means to cool a maser anti feed components, and achieve very low system noise temperatures. operation of' the maser near 1.7 K physical temperature instead of 4.5 K (as is used cm current DSN masers) dramatically improves its performance by both increasing its gain-bandwidth product and reducing its noise temperature from 3.8 K to about 1.0 K, Maser operation in superfluid liquid helium, below the 2. 17K "lambda point", increases performance two ways: 1) gain improves markedly (lowering noise temperature) as the superfluid provides an improved heat sink for the ruby, and 2) the super-ftuid heat sinks the ruby without "bubbling" or boiling, a fluid instability which adversely affects maser gain and phase stability. 'l'he feedhorn and other feed components can be cooled as well, reducing their noise temperature contributions to almost negligible levels.

The first X-hand 1.7 K liquid cooled ULNA maser was designed to provide the lowest possible Top. in April, 1989 a package employing a cryogenic feedhorn achieved maser operation at 1.7 K [Ref. 6].

The basic Block II-A maser design was modified to permit operation at 1.6 K physical temperature. As the electronic gain in decibels (excluding circuit losses) of a maser is approximately inversely proportional to the physical temperature, one maser structure which provides 10 dB net gain and 100 MHz of bandwidth at 4.5 K provided 45 dB net gain with 7S MHz of bandwidth at 1.7 K ('1'able 1.).

Operating temperature of 1.6 K was achieved by evacuating the helium vapor in the dewar. Two Leybold-Hereaus S65B TRIVAC pumps arc combined to produce a flow of 43 LPH (92 CFM) and reduce the vapor pressure. to less than 800 Pa (6 torr).

The increase in gain required a corresponding increase in maser isolation to prevent regeneration and oscillation. A new isolator strip was designed ant] fabricated that provides twice the Block 1 I-A isolator reverse loss. The new resonant isolators required 4 times the YIG volume of a Block II-A isolator because the efficiency was reduced as the isolator enlarged beyond the area of maximum circular polarization in the slow wave structure.

A smooth-wall dual mode feedhorn was fabricated as no satisfactory method of manufacturing a thin-wall stainless steel corrugated horn has been found. in this application a temperature gradient was present across the length of the horn, with 300 K at the aperture, and 1.65 K at the copper base. The 22 dBi cryogenic feedhorn was fabricated in two sections, with the smaller diameter 20.3 cm (8 in.) long section machined from copper to maintain its temperature isothermally with the bath temperature. As nearly 60% of the microwave loss of the feedhorn normally occurs in this section, cryogenically cooling this portion greatly reduces the total loss of the horn. The 33.9 cm (1 3.3 in.) long larger diameter portion of the horn was machined from stainless steel, to a thickness of. 15 cm (.060 ins.) to restrict heat leaking into the cryostat. The interior of the stainless steel horn section was copper plated to a thickness of 2.31 {-4 cm (90 microinches) to improve the electrical conductivity of the feedhorn. The cold helium gas evacuating the dewar removed heat entering the cryostat through the horn from heat exchanger screens attached to the horn. The heat leakage into the cryostat through the born was calculated to be ª 400 mW.

At JP1. the maser/feed package Top of 7.5 K (clear weather at zenith) was measured including the sky, feedhorn, and maser, the lowest X-Band Top ever measured. "The stability was within limits necessary for use by the DSN for tracking purposes (+/- 0.02 till gain and -I/ -0.30 phase during 10 seconds), Although 1.7K cold-running time was less than 8 hours, a decision was made to test the ULNA cm1)SS-13. The original design was modified by the addition of an ambient temperature extension to the feedhorn to increase the gain to 25 dBi and thereby reduce the angle of the antenna pattern (Jig. 7). This reduced the "spill over" noise visible by the LNA and provide.cl the feed a closer match to the beam waveguide antenna "optics". The complete feed assembly was tested on the JPL antenna range to assure proper ellipticity and symmetry,

The ULNA maser/feed package was operated on the ground outside 1)SS- 13 then installed on the antenna November, 1991. When tested on the ground it exhibited 43 c111 of gain with a bandwidth of 76 MHz (-3 dB). 'The total system noise temperature measured 6.8 K at 8475 MHz with the feedhorn looking at the "cold" sky (zenith). Subtracting cosmic background and calculated atmosphere noise contributions, the input noise temperature of the. maser feed assembly is calculated to be 1.7 K. The Top on the antenna was 14-15 K across 8400-8500 MHz including cosmic background and atmospheric noise contribut ions.

To increase the 1.7 K cold running, time and increase the usable bandwidth of the ULNA, it was converted from a cooled horn configuration to a 3.48 cm (1.369 in.) circular waveguide input package. A thin wall .0254 cm (.010 in) stainless steel circular waveguide input transmission line 40.64 cm (16 in,) long and a Eccofoam (tm Emmerson and Cummings, inc.) vacuum window was fabricated to allow use of an ambient temperature 25 dBi corrugated horn (fig. 8). The low heat leakage through the stainless steel has reduced the liquid helium consumption and extended the 1.7 K cold running time to over 24 hours. The cold helium gas evacuating the dewar removes heat entering the cryostat through the stai nless steel input line through heat exchanger screens attached to flanges along the length of the waveguide. The heat leakage into the cryostat through the input waveguide is calculated to be ª100 mW. The interior of the stainless steel input section was copper plated to a thickness of less than 2.3E-4 cm (90 microinches) to improve. the electrical conductivity. . The calculated noise temperature contribution of the input line is .7K when the 1.7K-300 K gradient is across its length (fig. 9).

ULNA Used with Goldstone Solar System Radar

Goldstone Solar System Radar (GSSR) typically uses the DSS- 1470 meter antenna in a "monostatic" configuration whereby the 450 kW X-Band transmitter is pulsed and the secondary reflector is rotated to focus the incoming radar echo minutes later at the. feedhorn of the receive-only maser. Radar mapping of Venus, Mm, and asteroids have been successfully performed with this procedure [Ref. 7].

The opportunity to employ the ULNA for reception of deep space signals came when asteroid Toutat is closel y crossed Earth orbit in November-December, 1992 [Ref. 8]. At its closest approach to Earth the round-trip light t ime was insufficient to rotate the secondary reflector to the maser feed before the arrival of the. echo, so "bi stat ic" operat ion with another antenna and receiver was necessary. The low noise performance of the ULNA at DSS-13 made this antenna the best choice for the receiving station. Radar imaging requires analysis of the changes in polarization of received echoes, so simultaneous RCP and LCP recept ion is necessary. A second identical ULNA maser amplifier channel, a polarizer, and an orthomode junction were added to the maser/fe.cd package. The waveguide components are copper and operate in the 1.7K environment, therefore the addit ional noise cont ribut ion is low, .01 K. It was also necessary to raise the maser gain bandpass to allow amplification at 8510 MHz, the GSSR frequency. As the TWM/SCM assembly was suspended from the cooled horn in the earlier version, supports made of thin wall .074 cm (.029 in.) G-10 fiberglass tubes were. used to suspend and insulate the maser from the ambient temperature dewar lid. The four G-10 t ubes allow <50 mW total heat leakage.

The ULNA maser was again tested on the ground outside the DSS-13 antenna before installat ion. The ground Top including sky, at mosphere and horn was 8.3 K. After subt racting the cosmic background and atmospheric noise contributions the dual-channel ambient horn ULNA mist temperature is calculated to be 3.6K referred to the feedhorn aperture.

The ULNA maser was installed on the 34 meter antenna and system noise temperature was measured at 14.2 K, including cosmic background and atmospheric noise cont ributions. This is compares favorably to the lowest X-Band Top of any DSN antenna, 14K at the 70 meter DSS-14 using the circular waveguide input, listen-only Block II-A maser.

CONCLUSION

The Block 11-A is the result of over 20 years of TWM/CCR development at JPL and includes man y refinements which enhance reliabilit y, add gain/bandwidt h, stabil it y, and improve low noise performance.

In July, 1993 the ULNA maser will be used for radar studies of Mercury. Refinements planned for this installation include installation of a lower loss circular waveguide vacuum window, and improved cryogenic temperature sensors.

Fut ure plans include conversion of the batch-fed liquid helium system to a dual-dewar continuously operating system. Also, development of a 1.7K liquid helium cryostat that can be tipped is planned, If a tippable liquid helium-mold maser similar to the ULNA could be installed on])SS-14 a total system operating temperature of about 11 K (zenith, clear weather) could be expected.

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REFERENCES

1. N. A. Renzetti and C. 'T'. Stelzried, "Introduction", JPL, Publication 82-104 *The Deep Space Network, a Radio Communications Instrument for Deep Space Exploration,* Jet Propulsion Laboratory, Pasadena, California

2. J. S. Shell, R. C. Clauss, S. M. Petty, G. W. Glass, M. S. Fiore, J. J. Kovatch, J. R. Loreman, D. E. Neff, R. B. Quinn and D. 'T'. Trowbridge, *Ruby Masers for Maximum G/Top,* Submitted for a special issue of Proceedings of the IEEE on the *Design and Instrumentation of Antennas for Deep Space Telecommunications and Radio* Astronomy, to be published November 1993

3. S. M. Petty and D. 'T'. Trowbridge, JPL, Publication 82-104 '*The Deep Space Network, a Radio Communications Instrument for Deep Space Exploration*

4. D. L. Trowbridge, "Block II-A Traveling Wave Maser", *TDA Progress Report* 42-87, Jet Propulsion Laboratory, Pasadena, California

5. A. E. Siegman, *Microwave Solid State Masers,* McGraw Hill, (1964)

6. D. L. Johnson, S. M. Petty, J. J. Kovatch and G. W. Glass, "Ultra-Low noise Performances of an 8.4 GHz Maser/Feedhorn System ", *TDA Progress Report* 42-100, Jet Propulsion Laboratory, Pasadena, California

7. J. D. Dvorsky, N. A. Renzetti, D. E. Fulton, JPL. Publication 92-29, *The Goldstone Solar System Radar, A Science Instrument for Planetary Research* Jet Propulsion Laboratory, Pasadena, California

8. "Scientists Get Close Look at Asteroid", *Los Angeles Times,* (January 4, 1993)

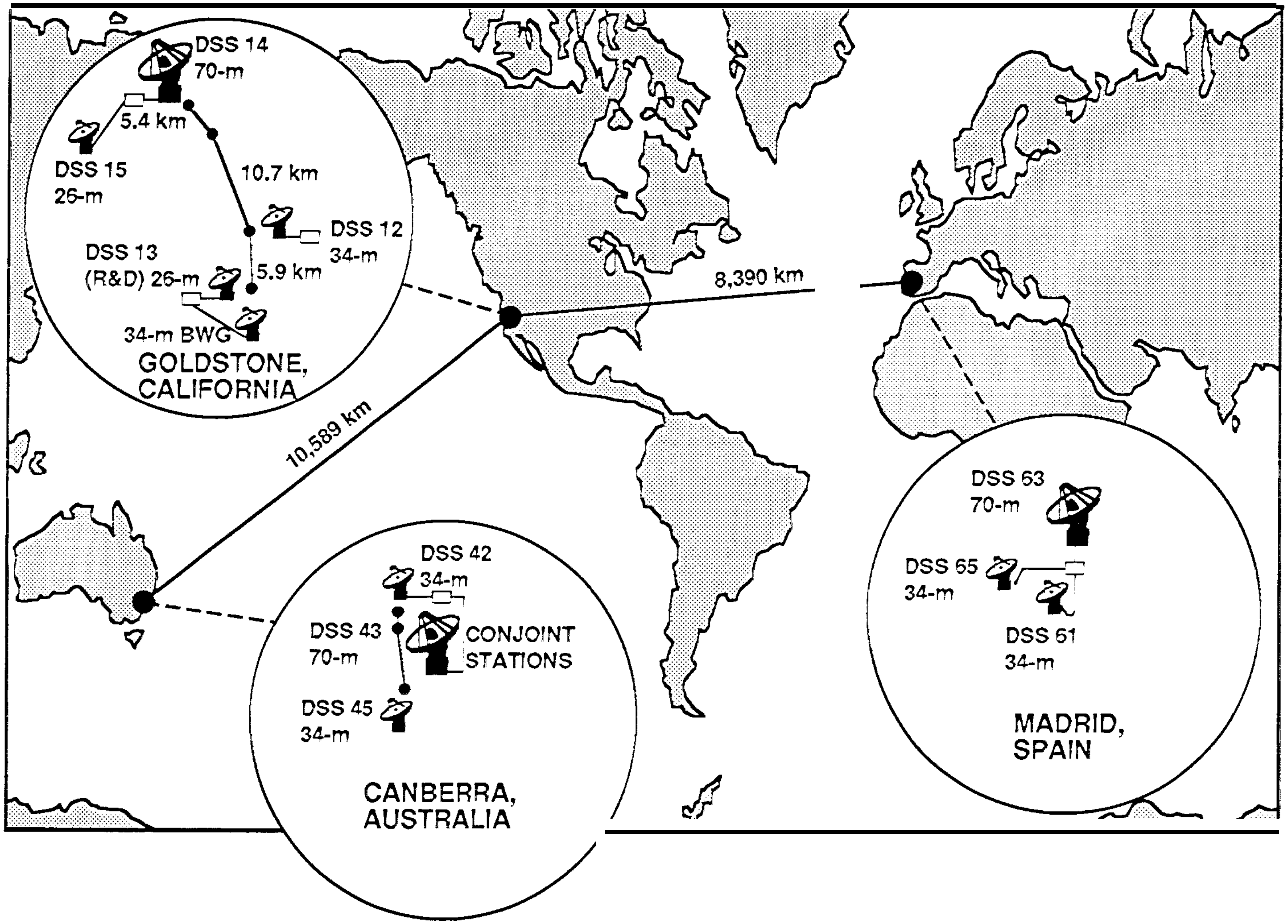


FIGURE 1. DEEP SPACE NETWORK COMPLEX CONFIGURATION

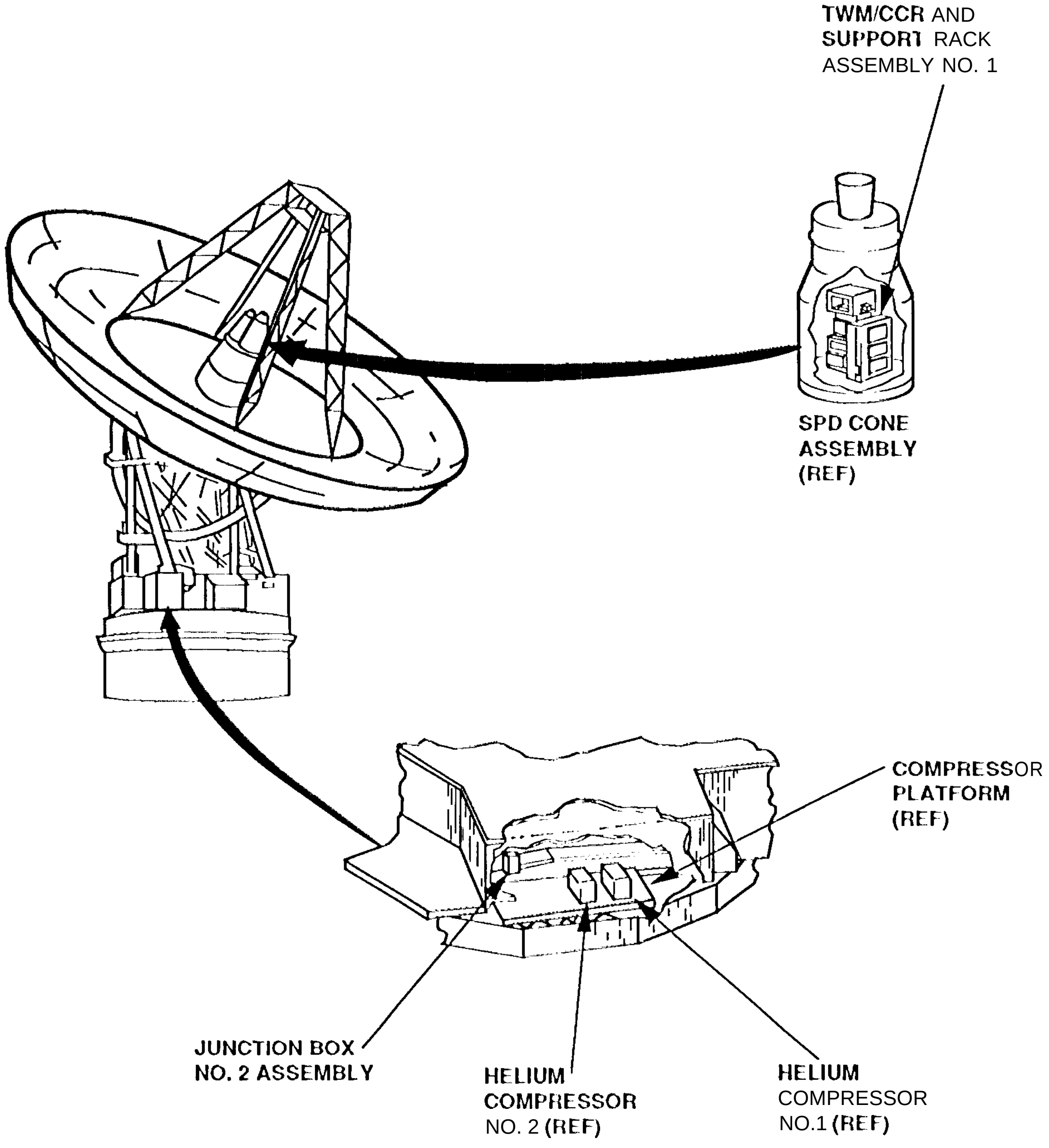


FIGURE 2. CONE HOUSING LNA's ON CASSEGRAIN 70m ANTENNA

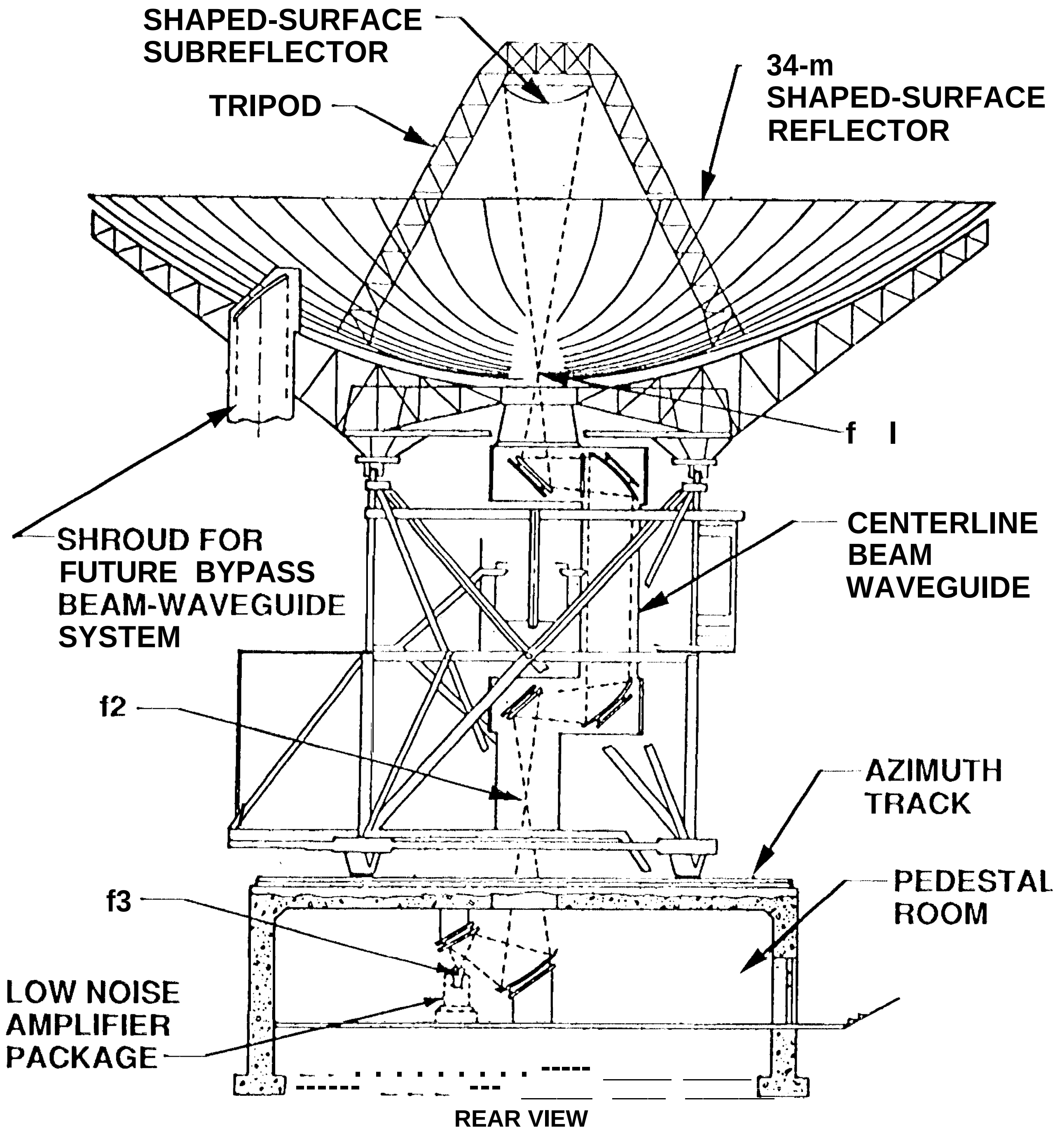
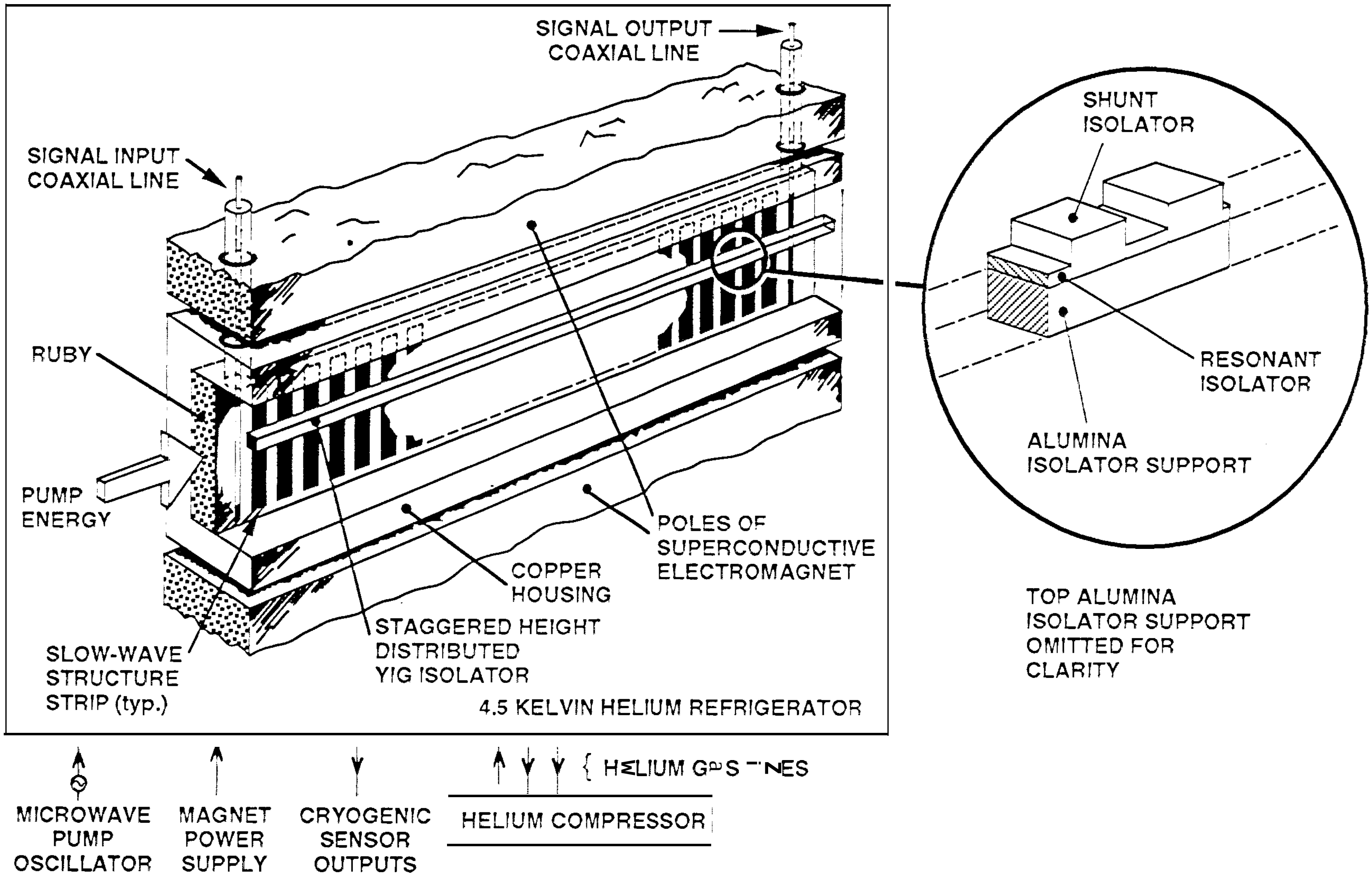


FIGURE 3. OUTLINE DRAWING OF DSS-13 BWG ANTENNA



Figu e 4 Schematic Diagram of Block IIA Maser

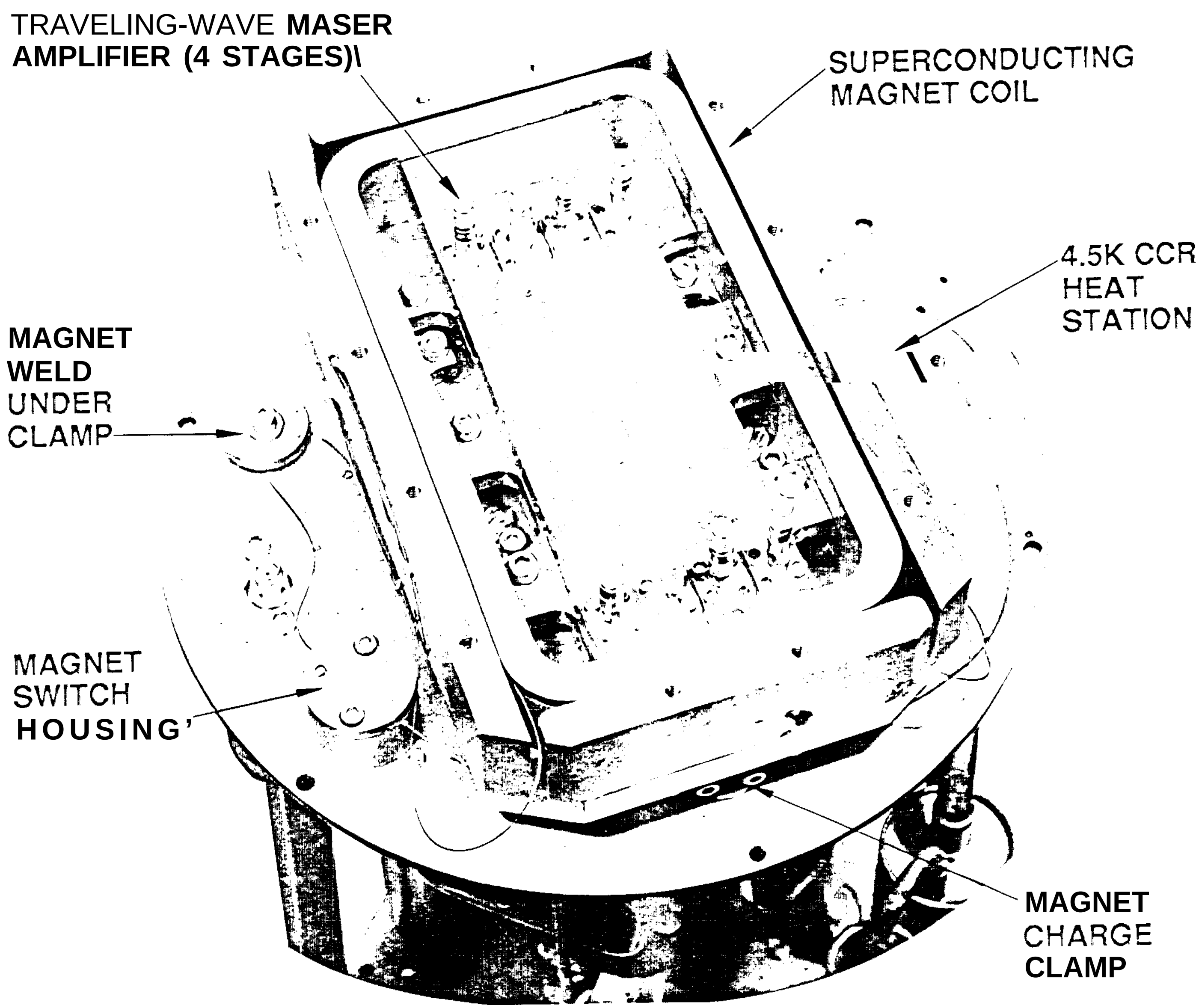


FIGURE 5. SUPERCONDUCTING MAGNET ASSEMBY (LID REMOVED)

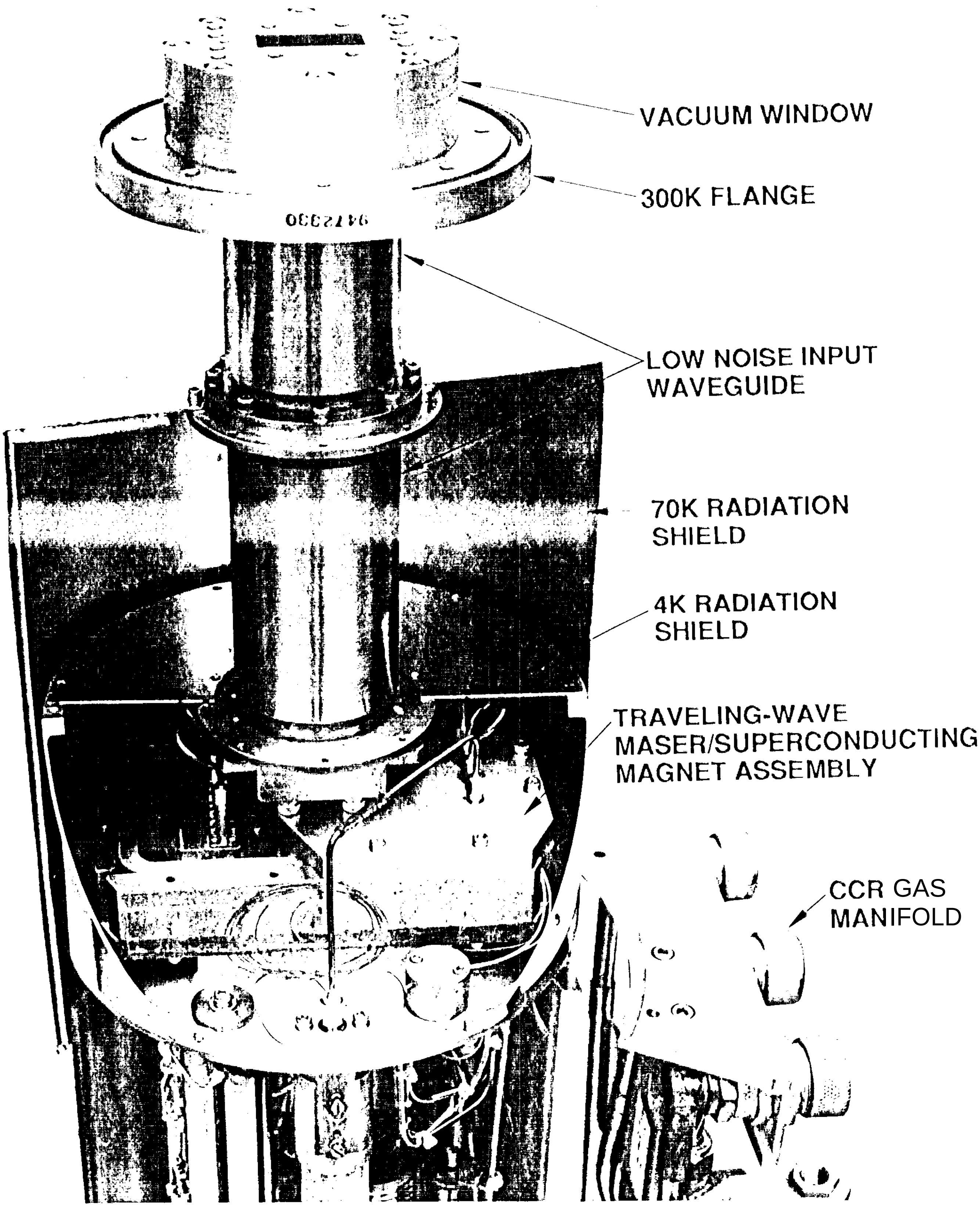


FIGURE 6. BLOCK IIA MASER WITH SPLIT SHIELD FOR CLARITY

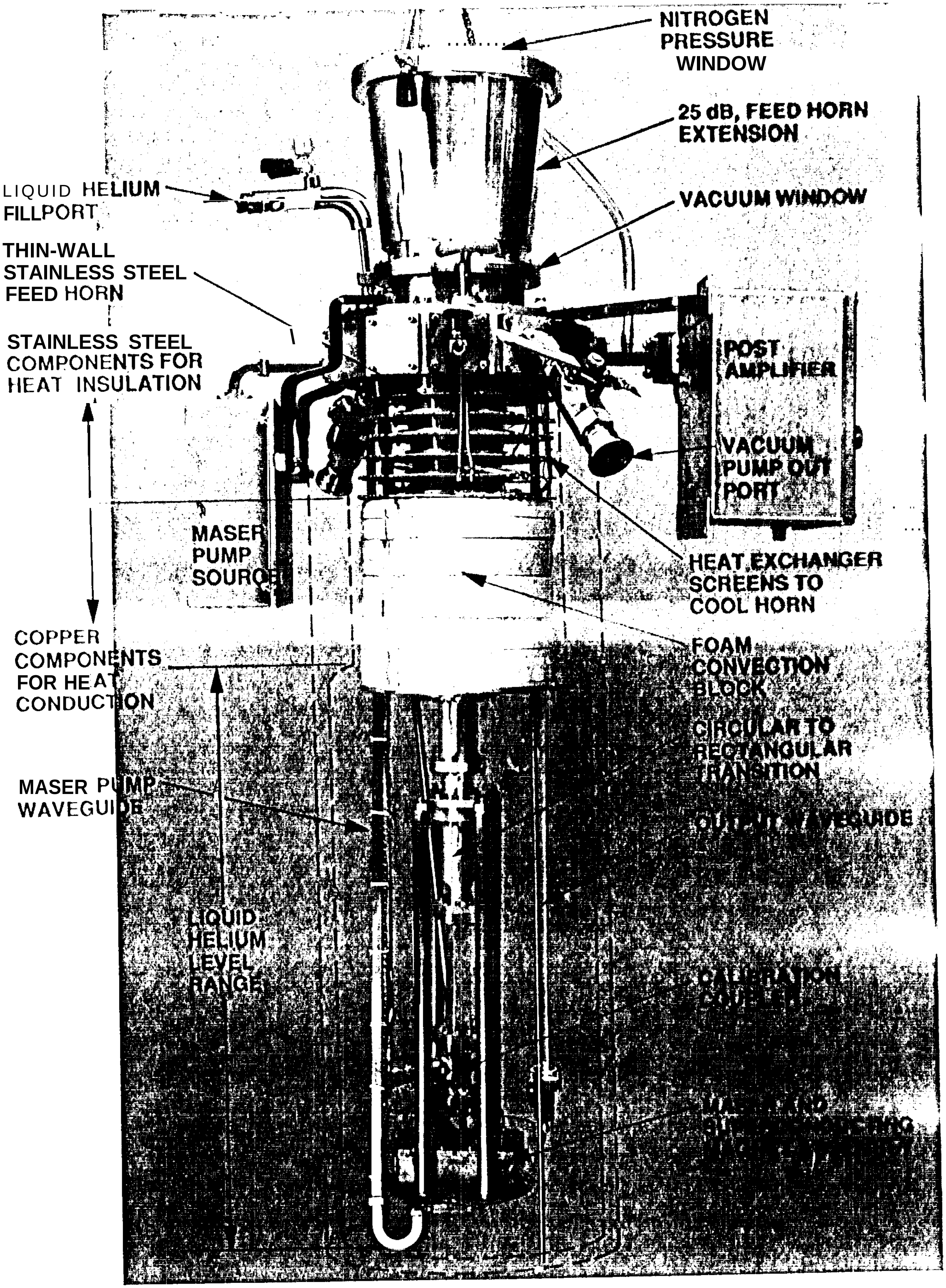


FIGURE X. X-BAND ULNA

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X-BAND ULNA

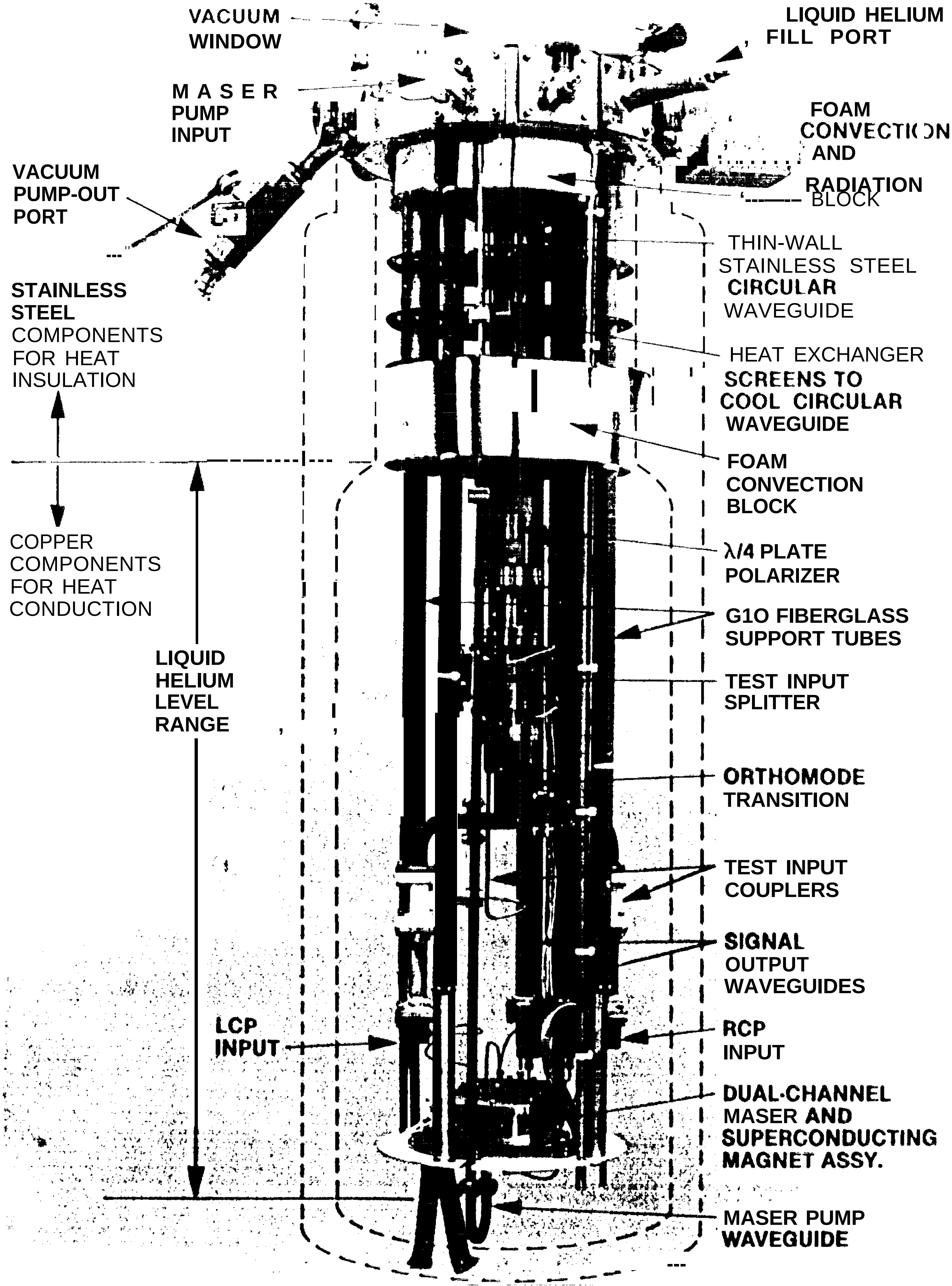

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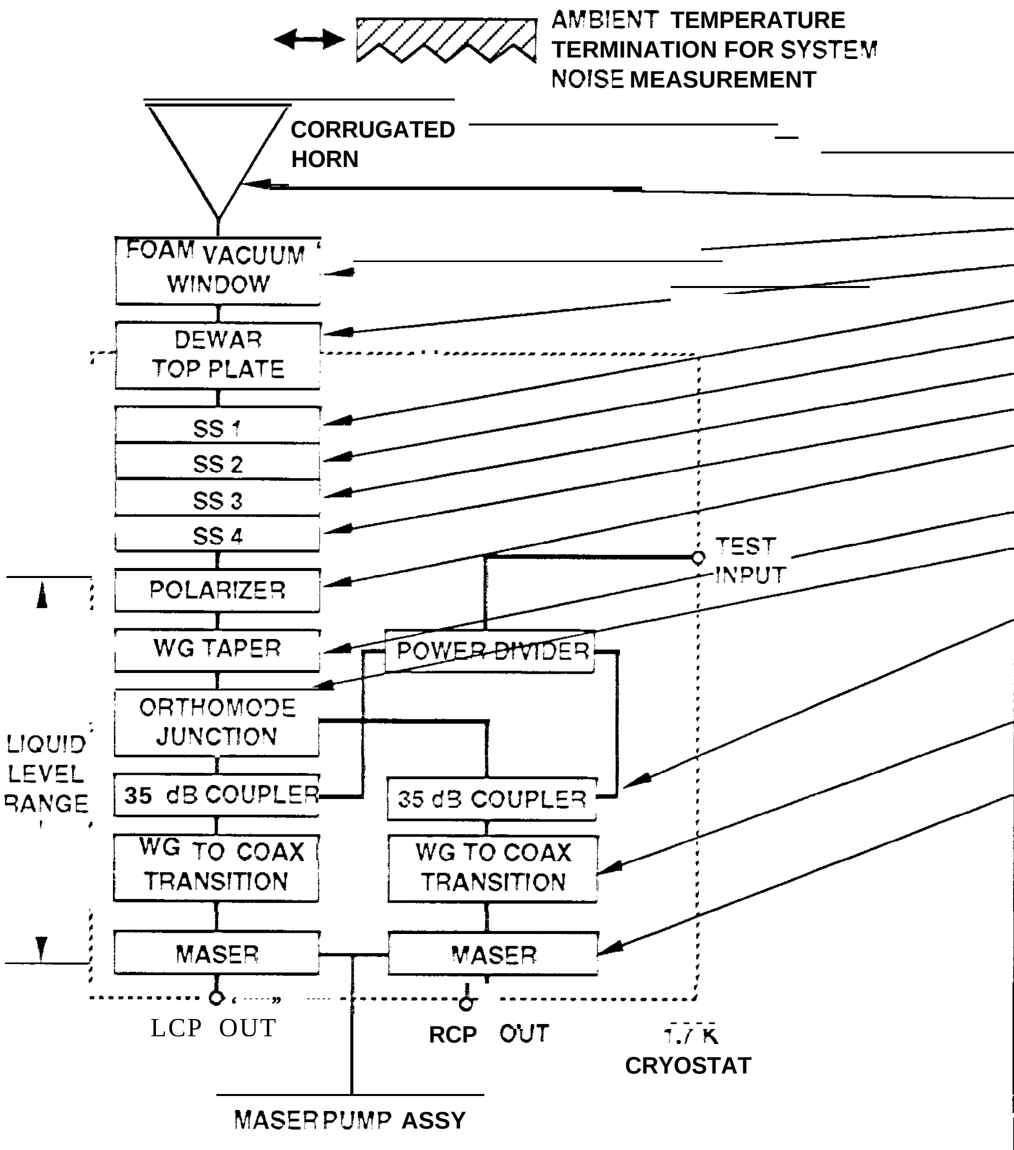
FIGURE 8,

BLOCK DIAGRAM AND NOISE BUDGET FOR DUAL-CHANNEL, WAVEGUIDE INPUT ULNA



ITEM	NOISE TERM (K)
INPUT MISMATCH LOSS	0.158
KAPTON WINDOW. 1.5 MIL	0.100
CORRUGATED FEEDHORN	0.200
HORN FLANGE ADAPT/VAC WINDOW	0.300
Al TOP PLATE	0.028
SS WC137 SECTION 1	0.293
Ss Wc 137 SECTION 2	0.214
Ss Wc 137 SECTION 3	0.133
Ss Wc 137 SECTION 4	0.052
WC137 POLARIZER SECTION	0.001
WC"37 WG	0.000
WC137/WC104 COSINE TAPER	0.001
ORTHOMODE JUNCTION	0.003
WR112 WG BEND	0.002
35 dB CALIB COUPLER (LOSS)	0.001
35 dB CALIB COUPLER (INJ NOISE)	0.096
W4112 WG STRAIGHT	0.002
WR112/SMA ADAPTER	0.002
0.141 inch DIA COAX LINE	0.006
MASER ASSEMBLY	1.200
CRYO OUTPUT COAX/WG ASS'Y	0.000
CRYO OUTPUT WG ASS'Y	0.00 ?
AMBIENT OUTPUT WG/COAX	0.005
HEMT POST AMP	0.045
TRANSMISSION LINE LOSS	0.000
RECEIVER ASSEMBLY	0.000
TOTAL CALC. INPUT NOISE TEMP.: (REF. TO APERTURE OF FEEDHORN)	2.85
MEASURED INPUT NOISE TEMP. : (REF. TO APERTURE OF FEEDHORN)	3.60

figure 9

Table 1. Performance of Block 11-A maser and liquid-cooled maser compared

	Typical DSN Block II-A Maser	Maser Developed for '1 his Demonstration
Center frequency, MI 17	8450	8475
Maser structure temperature, K	4.5[a]	1.7K
No. of 8.5-en] ruby-filled channels	4	1
Electronic gain/unit length, dB/cm	1.4	4.6
Ruby absorption (A), dB	16.2	17
Inversion ratio (1 = E /A)	3.()	2.8
Forward loss (copper and dielectric) (S), dB	7.5	2.5
Forward loss (due to isolator) Y, dB	1.5	2.5
'1 otal forward loss (f = S + Y), dB	9	5.()
1 otal isolator reverse loss, dB	150	74
Calculated maser input noise temperature	3.4	1.05
Net gain (G = E - F), dB	40	34
Bandwidth (-3 dB) MHz	107	100

[a] Ruby bars cooled by conduction in a vacuum. 1 herefore, actual ruby temperature is assumed to be 5. OK.